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Can perceptual learning compensate for optical image blur?

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A R T I C L E   I N F O

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A B S T R A C T

Tests of target recognition under blur mostly fail to separate factors of resolution and contrast from the influences of pure blur, i.e., shallow luminance edge gradients. In experiments designed to single out blur, patterns of fixed size were convolved with a Gaussian spread function whose parameter was the variable. In addition, contrast invariance was ensured. The spread parameter was varied to measure form discrimination thresholds for simple geometrical shapes. Following determination of baseline values, observers trained for 7 days, 1000 form discrimination responses with error feedback per day in a staircase procedure of the blur parameter. For four observers, thresholds improved an average of 5% (range −11% to +14%) equally for trained and untrained patterns and remained stable during subsequent training with the same targets in a related form discrimination task not involving blur. Because it transferred across target sets, the very slight improvement was indeed in the perceptual capacity to compensate for optical image degradation and not in form discrimination, but its defocus equivalent was quite minor, well less than ¼ diopter. Previous claims for blur adaptation must therefore rest on more complex factors that are not fully excluded in clinical settings.

1. Introduction

It has long been argued whether adaptation to blur can improve visual performance in target recognition of, say, uncorrected or undercorrected myopes or of observers viewing the world through blurring lenses. Examination of this question, often with a positive answer (George & Rosenfield, 2004; Mon-Williams et al., 1998; Pesudovs & Brennan, 1993) even if occasionally quite small (Cufflin, Mankowska, & Mallen, 2007), is carried out by visual acuity tests and dioptric blur, as indeed befits its clinical optometric relevance. When this leads to the hypothesis that the phenomenon has its origin in "perceptual adaptation …occurring in central sites within the visual cortex" (Rosenfield, Hong, & George, 2004), a more careful analysis is warranted to ensure that postulates of information transfer are obeyed, for target details not contained in the retinal image cannot truly be said to have been recognized. Perceptual learning has also been invoked in possible adaptation of normal observers to the inevitable image degradation by their ocular aberrations (Artal et al., 2004). Recent advances in adaptive optics techniques have enabled their cancellation with consequent improvement in visual acuity. Careful probing has revealed little if any perceptual adaptation to this long-standing image degradation (Rossi et al., 2007; Rossi & Roorda, 2010). The topic of perceptual learning with subsequent improvement in an observer's performance with blurred targets is therefore being re-examined here, this time by employing blur methodology without the confounding components inherent in the purely optical factors of dioptric defocus and retinal ones of resolution and contrast impairment.

Blur, the subjective manifestation of image degradation, is of primary consequence in impairing object recognition; its investigation therefore necessarily involves the perception of form and, in psychophysical approaches, form discrimination thresholds. Although it has long been known to transcend resolution and visual acuity, the form sense is still largely probed by the traditional visual acuity charts. The more recent sine-wave grating or Gabor patch tests have the intrinsic disadvantage of lacking crisp borders whose smearing is the essential criterion of the transition from sharpness to blur and between different levels of blur. Border sharpness requires the fullest available spatial frequency spectrum, which by definition is severely restricted in such tests.

For this reason, the case has recently been made for a Gaussian spread convolution of targets as a means of measuring form discrimination thresholds (Westheimer, 2013). It is employed here to investigate the extent to which perceptual learning can influence performance. Rather than leaving the target sharp and counting on the eye and possible associated optics to produce the blur, the procedure is reversed. Good focus is retained on a target plane in which blur is generated in a precisely regulated manner and used as the psychophysical variable.

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2. Methods

2.1. Targets

Patterns were chosen to concentrate on form discrimination in rigorous threshold procedures. They were pentagons pointing in one of the four cardinal directions and thus differing only in the form of their outline and not in area, contour length, or any other major property (Fig. 1 upper). A second set required the binary choice between a square and an octagon, with a difference again only in shape and not area and very little in contour length (Fig. 1, lower). Each run featured patterns belonging to only one of these sets, but the selections within the set was always random. Observers quickly learned to associate target direction or class with computer keyboard arrow keys.

Dark targets on a medium photopic white background ($\sim$200 cd/m^2), each 15–20 arcmin in diameter and composed of pixels 1 arcmin in size, were employed; dimensions remained invariant throughout the study. The experimental variable was the parameter k of the Gaussian spread function $(1 - \exp - (r/k)^2)$ with which each target pixel was convolved. The resultant pixel map was normalized to give its darkest point half the luminance of the background, i.e., Michelson contrast of 0.33, which also remained invariant. Gamma linearization ensured luminance fidelity to the calculated light gradients. The pixel maps thus specified – pattern orientation, Gaussian parameter, contrast normalization and gamma correction – were computed on-line for each trial with a program written in Java. Targets were presented in the center of a 40 arcmin diameter bright disk (Fig. 2) whose sharp border facilitated foveal fixation and focus stabilization, and were exposed until the observer's keyboard press registered the response and initiated the next display. Observation was binocular on standard laptop screens at distances in each case such that a pixel subtended one arcmin. The display methodology is described in fuller details in Westheimer (2013),

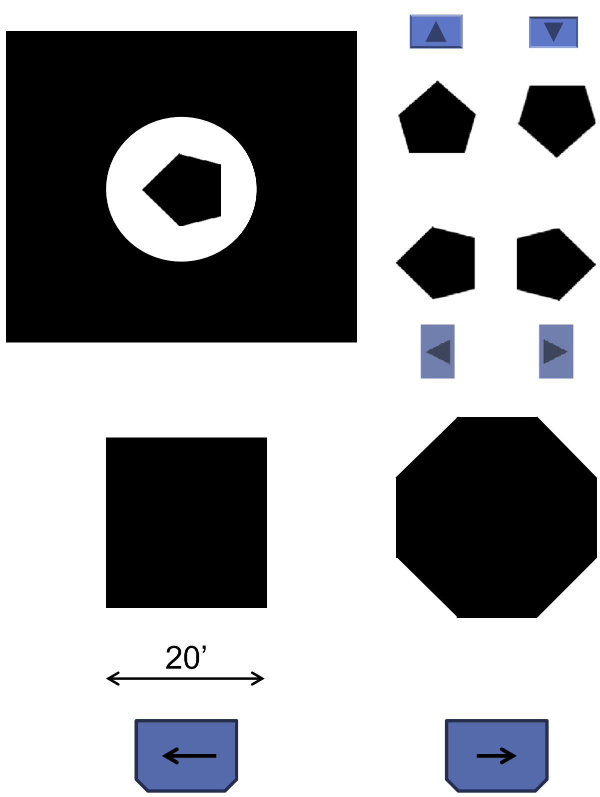

Fig. 1. Forms used in the experiment. Upper: Identical pentagons pointing in one of four directions, left, right, up and down, and the keyboard arrow keys associated with correct responses. Lower: Square and octagon of identical area with almost identical total perimeter lengths, and their associated response keys. All patterns were composed of pixels each subtending 1 arcmin at the observer's eye and each pixel was convolved with a Gaussian spread function. After contrast normalization to a Michelson value of 0.33 and gamma correction, the convolution was displayed on laptop monitors (see Fig. 2).

2.2. Threshold measurements

A staircase procedure was used to determine the Gaussian parameter with which individual patterns had to be convolved for threshold target recognition. In each presentation one member of the target set, selected at random, was shown with the blur predicated by the staircase progression (Fig. 2), and the observer had to respond, if necessary by guessing. In sequential presentations, the value of the parameter was reduced (target appearance sharpened) until responses were reliably correct (3 in a row for 4-alternative choices, 5 for two alternative), and then increased until responses were random, and so on. For base-line data no error feedback was provided; the first three reversal of the staircase were ignored, and the parameter values of the next 12 reversals were used for calculation of a mean and its standard error. The rate of convergence of the staircases is indicated by the fact that this required usually of the order of 150–180 individual responses. The procedure was repeated once on the same day, and twice on the next, and the average of the four means was taken as the threshold blur for form discrimination. The significance of differences of mean averages was examined by t-tests.

2.3. Training procedure

After base-line threshold data were secured for all conditions to be later compared, the observers followed a daily regime of 1000 responses in a single long staircase with error feedback. There were usually about 150 or more reversals in the runs, which lasted 30–40 min and were devoted to only the pentagon set of patterns. For informational purposes, the means of the reversals was noted. Following 7 days of training, the base-line threshold determinations were repeated. There followed another 7 days of training, using

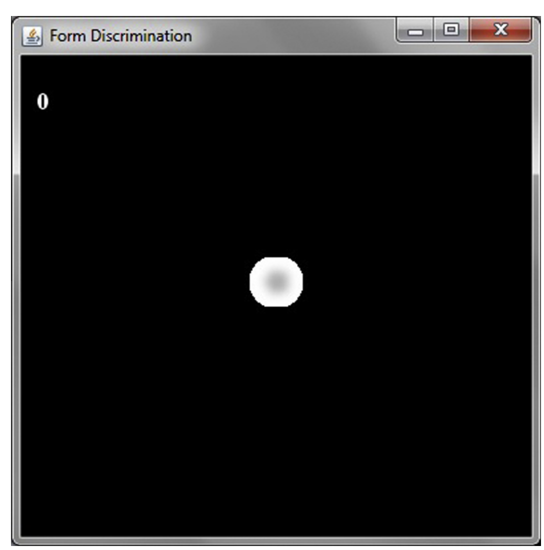

Fig. 2. Observers' view of screen, showing a circular contour in sharp focus in the center of which the blurred configuration was displayed. Observers had to indicate, if necessary by guessing, the orientation of the blurred pentagon. By means of a staircase psychophysical procedure, the parameter of the convolving Gaussian spread for discrimination threshold of the patterns' orientation was determined.

the same patterns and training procedure, but this time the challenge to target recognition was not blur but added noise (proportion of corrupted pixels in otherwise sharp images). A final repeat of the base-line threshold measurements enabled some conclusions about the stability of training improvement, if any, and whether it might be attributed to the perception of blur or to form discrimination of the set being used.

2.4. Observers

Four observers participated in the study including three undergraduate biology students naïve to the project with no previous experience in visual psychophysical research. For purposes of this work with targets 15–20 arcmin in size, presented against a background luminance of 200–300 cd/m^2 with Michelson contrast of 0.33 and unlimited observation time, the observer's optometric status was unexceptional. Inter-observer variations are common in learning research, but four participants were deemed sufficient here when their individual results showed such high concordance. The study was approved by the institution's human subject review board and complied with the Helsinki declaration.

3. Results

The results of the investigation are presented in Table 1 and Fig. 3, the average for all observers. It is seen that.

1. Training improved performance very slightly.
2. The improvement, such as it was, transferred to a similar pattern ensemble not trained on, implying that what was learned was not to discriminate form but to overcome blur.
3. Further training in a related task, distinguishing form when handicapped by noise, left thresholds unchanged, showing stability of the changes and also that it was perception not *of form* but *within blur* that had been improved.

There was a gratifying agreement of the findings across all four observers (Fig. 4 and Table 2). Statistical significance varies somewhat, but in no case does the substantial training regime lead to anything but a minor improvement of performance.

4. Discussion

It is generally agreed that when observers' perceptual performance improves as a result of training, some changes have taken place in cortical circuitry. Because there is great interest in cortical plasticity, a claim for perceptual learning needs a solid foundation before it can be accepted that the function in question involves cortical and not, say, retinal processing and a search is entrained for the responsible cortical apparatus. Reports on the ability to null out the visual decrement due to uncorrected refractive error, referred to as blur adaptation, have a long history. If it were indeed the degraded retinal light distribution on which the claims for perceptual learning centered, then one could proceed to study what plasticity this might manifest in "early" visual processing, that is,

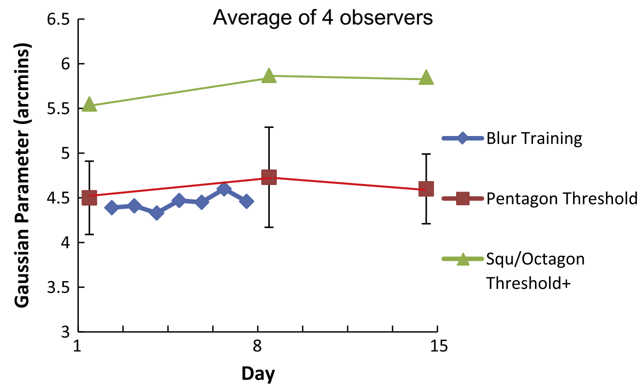

Fig. 3. Parameter of convolving Gaussian spread for orientation discrimination of pentagons (Fig. 1 upper) before, during and after 7 days of training with pentagons, and then after 7 days of training on an unrelated discrimination task also with the pentagon target. Also shown are the thresholds for an untrained task, discriminating between a square and an octagon (Fig. 1, lower). Mean for all observers.

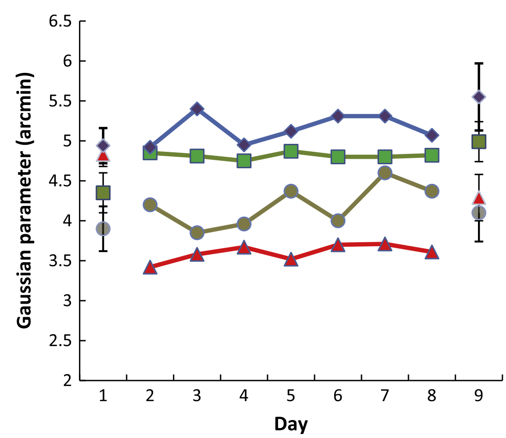

Fig. 4. Before, during and after training data, as in Fig. 3, shown separately for each observer. Left: baseline data for each of the observers. Days 2–8: thresholds for 1000 trials with feedback during 7 days of training on blur discrimination with pentagons, for each of the four observers. Right: Thresholds after blur training for each observer, with procedure identical to baseline data, showing almost no improvement as a result of training. The higher the value of the Gaussian parameter, the more resilient form perception to blur degradation.

at the beginning of the visual stream as it enters the central nervous system. But, when blur adaptation is dealt with in clinical settings, a host of factors enter that are difficult to control and may instead implicate mechanisms other than just learning to "deblur" a degraded image. They include the variations in the state of the patient's accommodation and pupil, familiarity with test patterns, the resolution component in Snellen acuity measurements, test methodology, and so on. The potential for patients to profit from detailed examination of their retinal image, to call on memory traces, guesses and intuition or to manipulate their intra- and extra-ocular musculature for purposes of correctly calling letters on

Table 1
Parameter of Gaussian Spread for form discrimination threshold, average of all observer, in arcmin, before and after 7 days of training with blurred pentagons and after 7 days of subsequent training with noise-degraded pentagons. Also shown are the after/before training ratio (learning) and an indicator of retention.

Threshold Gaussian (arcmin)					
Test target	Before blur training A	After blur training B	Learning ratio B/A	After noise training C	Retention ratio C/B
Pentagons	4.50	4.73	1.05	4.60	0.97
Sq/Octagon	5.55	5.87	1.06	5.85	1.00

Table 2
Parameter of Gaussian Spread for form discrimination threshold for all observers, before and after 7 days of training with blurred pentagons and then after 7 days of subsequent training with noise-degraded pentagons.

Threshold Gaussian (arcmins)						
Observer	Before blur training A	After blur training B	Learning ratio B/A	Significance	After noise training C	Retention ratio C/B
I	4.35 ± 0.34	4.99 ± 0.25	1.15	$p = 0.03^{*}$	4.93 ± 0.15	0.98
II	3.90 ± 0.28	4.10 ± 0.36	1.05	$p < 0.1$	4.35 ± 0.35	1.06
III	4.94 ± 0.22	5.55 ± 0.42	1.12	$p = 0.05^{*}$	5.05 ± 0.22	0.91
IV	4.83 ± 0.15	4.29 ± 0.29	0.89	$p = 0.01^{**}$	4.10 ± 0.27	0.96

a visual acuity chart need not be denied. The topic here is different, whether blur *qua* blur can yield to perceptual learning.

Of specific relevance is the fact that defocus, the traditional yet reversible cause for blurred vision in this context, produces a complex retinal light distribution characterized by an optical transfer function that does not decrease monotonically to zero but instead allows for the possibility of spurious resolution.

By keeping target size and contrast constant throughout and using a Gaussian instead of a top-hat blur convoluting spread, the design of the present experiments avoided most of these complications and allowed concentration on the effect of just image degradation on form discrimination.

The resulting retinal image differences are basically in the realm of degraded target edge contours. That image blur and, to some extent, the nature of the blur, is being detected and utilized in control of the eye's axial length, is an implication in many current studies in myopia. But what is in play here is something else: distinguishing subtle contour differences in blurred targets. To satisfy the inescapable precondition of learning, it would have to be presumed that they were present all along but needed many presentations with error identification to learn to be recognized. Though the differences in degradation would, of course, have to have been encoded in differences in retinal ganglion cell discharges, the apparatus for detecting the subtle differences and that might be subject to perceptual learning would surely be cortical.

The minimal magnitude of the involved changes is a clue, and so is the time course, because spectacle blur adaptation has been convincingly demonstrated to take place in just a few minutes (Khan et al., 2013). There is the additional factor that the unit of measurement here employed, the parameter of the convoluting Gaussian spread in arcminutes, has to be related to the clinical measure of defocus, in which most earlier research in this area is expressed. An approximate conversion factor can be estimated via the respective Snellen acuity decrements. A 20/60 Snellen letter, the expected visual acuity in 1.0–1.5 diopter uncorrected myopia (Hirsch, 1945; Laurence, 1926; Smith, 1991), is equally placed at recognition threshold when convolved with a Gaussian spread of 5–6 arcmin. Hence the small average blur compensation with perceptual training found here, even were it statistically significant, would be well under 1/4 diopter defocus. This is consonant with some of the detailed studies of blur adaptation (Cufflin, Mankowska, & Mallen, 2007). But its small magnitude allows the conclusion that cortical mechanisms of perceptual learning do not play any significant role in compensating for purely optical spread in retinal image degradation.

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References

Artal, P., Chen, L., Fernández, E. J., Singer, B., Manzanera, S., & Williams, D. R. (2004). Neural compensation for the eye's optical aberrations. *Journal of Vision, 4*(4), 281–287. http://dx.doi.org/10.1167/4.4.4. article no. 4. <http://journalofvision.org/4/4/4/>.

Cufflin, M. P., Mankowska, A., & Mallen, E. A. H. (2007). Effect of blur adaptation on blur sensitivity and discrimination in emmetropes and myopes. *Investigative Ophthalmology & Visual Science, 48*, 2932–2939.

George, S., & Rosenfield, M. (2004). Blur adaptation and myopia. *Optometry and Vision Science, 81*, 543–547.

Hirsch, M. J. (1945). Relation of visual acuity and myopia. *AMA Archives of Ophthalmology, 34*, 418–421.

Khan, K. A., Dawson, K., Mankowska, A., Cufflin, M. P., & Mallen, E. A. (2013). The time course of blur adaptation in emmetropes and myopes. *Ophthalmic and Physiological Optics, 33*(3), 305–310. http://dx.doi.org/10.1111/opo.12031.

Laurence, L. (1926). *Visual optics and sight testing* (3rd ed.). London: School of Optics.

Mon-Williams, M., Tresilian, J. R., Strang, N. C., & Wann, J. P. (1998). Improving vision: Neural compensation for optical defocus. *Proceedings of the Royal Society of Biological Science, 265*(1390), 71–77.

Pesudovs, K., & Brennan, N. A. (1993). Decreased uncorrected vision after a period of distance fixation with spectacle wear. *Optometry and Vision Science, 70*(7), 528–531.

Rosenfield, M., Hong, S. E., & George, S. (2004). Blur adaptation in myopes. *Optometry and Vision Science, 81*(9), 657–662.

Rossi, E. A., & Roorda, A. (2010). Is visual resolution after adaptive optics correction susceptible to perceptual learning? *Journal of Vision, 10*(12), 11. http://dx.doi.org/10.1167/10.12.11.

Rossi, E. A., Weiser, P., Tarrant, J., & Roorda, A. (2007). Visual performance in emmetropia and low myopia after correction of high-order aberrations. *Journal of Vision, 27*(8), 14. article no. 7.

Smith, G. (1991). Relation between spherical refractive error and visual acuity. *Optometry and Vision Science, 68*, 591–598.

Westheimer, G. (2013). Measuring visual form discrimination with Blur thresholds. *Journal of Vision, 13*(5), 1–11, pii: 13. 10.1167/13.5.13. <http://journalofvision.org/13/5/13/>.